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Design of Feedforward Controller to Reduce Force Ripple for Linear Motor using Halbach Magnet Array with T Shape Magnet

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Abstract

Recently, in micro/nano fabrication equipments, linear motors are widely used as an actuator to position workpiece, machining tool and measurement head. To control them faster and more precise, the motor should have high actuating force and small force ripple. High actuating force enable us to more workpiece with high acceleration. Eventually, it may provide higher throughput. Force ripple gives detrimental effect on the precision and tracking performance of the equipments. In order to accomplish more precise motion, it is important to make lower the force ripple. Force ripple is categorized into cogging and mutual ripple. First is dependent on the shape of magnets and/or core. The second is not dependent on them but dependent on current commutation. In this work, coreless mover i.e. coil winding is applied to the linear motor to avoid the cogging ripple. Therefore, the mutual ripple is only considered to be minimized. Ideal Halbach magnet array has continuously varying magnetization. The THMA (Halbach magnet array with T shape magnets) is proposed to approximate the ideal one. The THMA can not produce ideal sinusoidal flux, therefore, the linear motor with THMA and sinusoidal commutation of current generates the mutual force ripple. In this paper, in order to compensate mutual force ripple by feedforward(FF) controller, we calculate the optimized commutation of input current. The ripple is lower than 1.17 % of actuating force if the commutation current agree with the magnetic flux from THMA. The performance of feedforward(FF) controller is verified by experiment.

1. Introduction

Recently, in micro/nano fabrication equipments, linear motors are widely used as an actuator to position workpiece, machining tool and measurement head. To control them faster and more precise, high actuating force and small force ripple is demanded for the linear motors.

Many researchers have studied improving performance of linear motor. The main problem in improving the tracking performance of linear motors is the presence of force ripple caused by mismatched current shape , unbalanced motor phases or amplifier gains [1,2]. They proposed a method to optimize the shape of the phase

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currents in order to reduce force ripple. The optimized current shapes generate minimal copper losses and maximize motor efficiency. Benjamin J. Paul suggested that torque ripple results from irregular magnetic field of permanent magnets and disharmony of current phase. He applied PID controller using torque sensor but it has disadvantage that BLDC (Brushless DC electric) motor is modified in order to install torque sensor and it costs a lot [3]. An adaptive control scheme proposed to reduce force ripple effects impeding motion accuracy in Permanent Magnet Linear Motors (PMLMs) [4].

In this paper, we use THMA (Halbach magnet array with T shape magnet) linear motor. This motor has high actuating force and small ripple force. To gain larger actuating force with THMA, Authors performed the optimal design of THMA linear motor [5]. THMA is easy to manufacture and assembly, however, it has nonsinusoidal flux distribution which result in force ripple. Generally, the nonsinusoidal flux distribution generates 6^{th} and 12^{th} harmonic force ripple [3,7].

Specially, force ripple causes tracking error and velocity ripple. In this paper, after calculating force ripple component using FFT (fast fourier transform), we design FF controller in order to reduce current ripple. It is robust to uncertainty of system and disturbance.

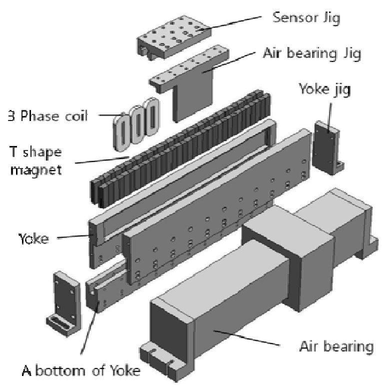

Fig. 1 Exploded view of the linear motor with THMA

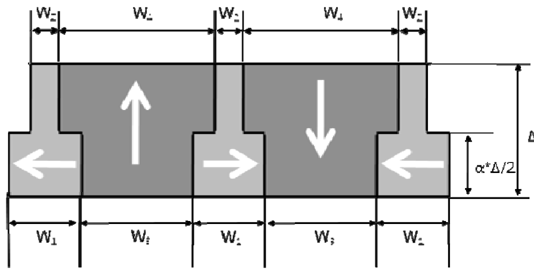

Fig. 2 Design parameter of THMA

2. Linear motor with THMA

Authors presented the linear motor with THMA as shown in Fig. 1 and 2 [5]. When we constructed the linear motion system, the following principles were taken into consideration: Abbe's principle and Bryan's alignment principle[6]. It consists of permanent magnet and coreless coil which is concentrated coil winding. The concentrated coil winding has some characteristics. It has enough width so it secures many number of turns of coil. It also strong to thermal change because generated heat of the concentrated coil winding is dissipated though the air gap. The linear motor with THMA has higher actuating force and smaller force ripple than conventional linear motor. The optimizied linear motor with THMA produces higher force per unit mass. It is enhanced over 24.8 %. Mean force of the linear motor with THMA increases with 8.2 %.

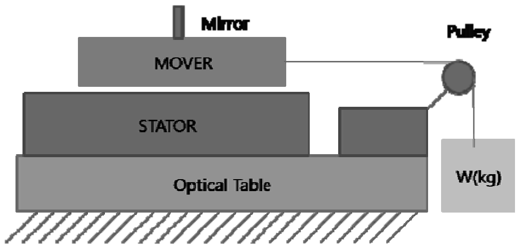

Fig. 3 Experiment setup

$$S_A = \sum_{n}^{1,3,5...} S_n \cos n\theta \qquad I_A = I_0 \cos\theta$$
$$S_{A'} = \sum_{n}^{1,3,5...} S_n \cos(n\theta + \frac{2\pi}{3}) \qquad I_{A'} = -I_0 \cos\theta$$
$$S_B = \sum_{n}^{1,3,5...} S_n \cos(n\theta - \frac{2\pi}{3}) \qquad I_B = I_0 \cos(\theta - \frac{2\pi}{3})$$
$$S_{B'} = \sum_{n}^{1,3,5...} S_n \cos n\theta \qquad I_{B'} = -I_0 \cos(\theta - \frac{2\pi}{3}) \qquad (1)$$
$$S_C = \sum_{n}^{1,3,5...} S_n \cos(n\theta + \frac{2\pi}{3}) \qquad I_C = I_0 \cos(\theta + \frac{2\pi}{3})$$
$$S_{C'} = \sum_{n}^{1,3,5...} S_n \cos(n\theta - \frac{2\pi}{3}) \qquad I_{C'} = -I_0 \cos(\theta - \frac{2\pi}{3})$$

$$F = [I_A \quad I_B \quad I_C \quad I_{A'} \quad I_{B'} \quad I_{C'}][S_A \quad S_B \quad S_C \quad S_{A'} \quad S_{B'} \quad S_{C'}]^T \qquad (2)$$

$$I_0 = \sum_{k}^{1,2,6} (I_k \cos k\theta + I_k \sin k\theta) \qquad (3)$$

$$where \quad \theta = 2\pi x / p$$

3. Experiment set-up

The linear motor is guided by a linear air bearing. The position is measured by a laser sensor (RLU10 from Renishaw Inc.) which has high resolution of 20 nm. The linear motion system is controlled by a DSP (Digital signal processor, DS1005 from dSPACE).

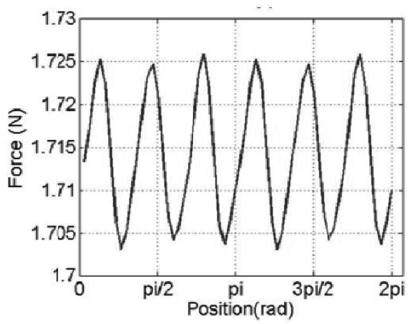

Fig. 4 Force ripple calculated from magnetic flux

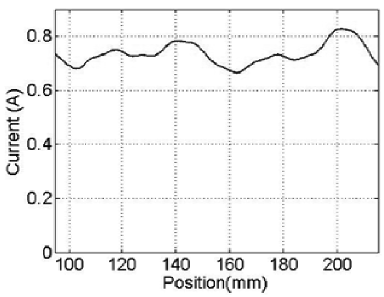

Fig. 5 Current ripple (W=4 kg)

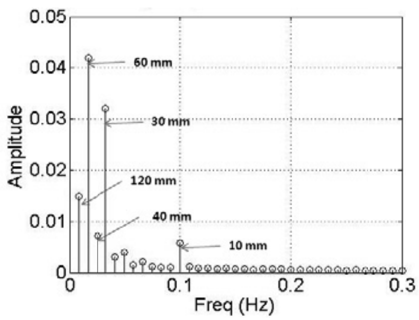

Fig. 6 FFT of current ripple (W=4 kg)

In order to measure force and current ripple, a weight (W) was engaged to the linear motion system as shown in Fig. 3. We calculate force in Eq. (2) ripple caused by magnetic flux using Fouier series in Eq. (1). Fig. 4 shows force ripple of 6^{th} and 12^{th} harmonics. The current mismatch generates force ripple of 1^{st}, 2^{nd}, 6^{th} and 12^{th} [3,7]. Mutual force ripple is proportional to the current. The ripple is lower than 1.17 % of actuating force provided that current is sinusoidal as presented in Eq. (1).

To position the linear motor against the weight, TDC controller was used as shown in Fig. 7 without FF controller. For every position input current amplitude (I_0) is measured as dipicted in Fig. 5.

1^{st} harmonics is from the sinusoidal current with offset. 2^{nd} harmonics result from amplitude of current, and 6^{th} harmonics and 12^{th} harmonics are caused by magnetic flux variation from sinusoid in air gap. Some researcher have tried to eliminate force ripple caused by irregular current. They proposed driving method of new type linear motor. It consist of power amplifier per each of phase current [9]. our system only consist of one power amplifier per 3 phase current. Fig. 6 shows current ripple of 1^{st} (60 mm), 2^{nd} (30 mm), 6^{th} (10 mm) and 12^{th} (5mm) harmonics component. But 12^{th} harmonic component is very small. $2/3^{th}$ (40 mm) and $1/2^{th}$ (120 mm) harmonics component result from unknown manufacturing error.

4. Feed forward controller

Current ripple is modeled using Fourier series as shown in Eq. (3). Each of phase coil is energized using the negative value of I_o. This commutation makes lower the current ripple as shown in Fig. 8. Also the FFT component of Fig. 8 is presented in Fig. 9.

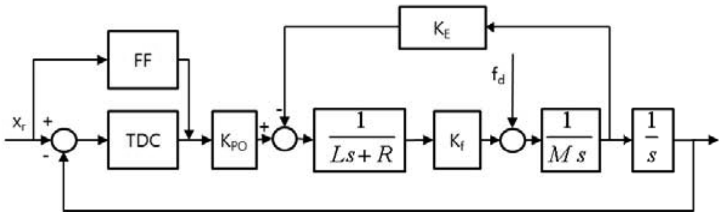

Fig.7 Block Diagram with THMA linear motor

K_{po} : Power amplifier gain
L : Motor inductance
K_f : Force constant
K_E : Back EMF constant
i : Motor electric current
R : Resistance of motor coil
f_d : disturbance

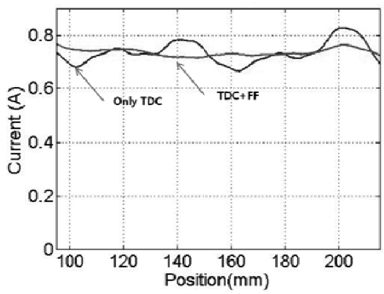

Fig.8 Current ripple compensated

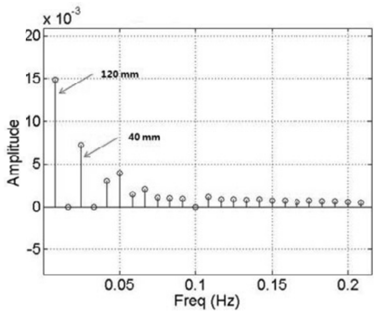

Fig.9 FFT of current ripple compansated

The results are from the simulation using Matlab™. We employed TDC(Time Delay Control) that is one of robust control and FF control. After we measured current ripple, current ripple was assumed by fourier Series. And we decrease current ripple calculated by MATLAB^{TM}. In Fig.10 we can find that 1st , 2nd and 6th harmonics component is eliminated.

5. Conclusion

In this paper, FF control to reduce force ripple for linear motor with THMA is proposed. THMA has high actuating force and small force ripple. The force ripple deteriorates the tracking performances and makes periodic position error. We measure current ripple and compensate current ripple using FF control. We suggest the control scheme which is composed of TDC control and FF control.

First, force ripple is lower than 1.17 % of actuating force provided that current is ideal. But current is not ideal so actually force ripple is higher than 1.17 %.

Second, we analyze FFT of current ripple and find harmonic components that have effect on current ripple and eliminate it.

In the future, we need to verify compensation of force ripple.

Acknowledgement

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